

Research article

An integrated modeling approach for estimating hydrologic responses to future urbanization and climate changes in a mixed-use midwestern watershed



Michael G. Sunde^{a,*}, Hong S. He^a, Jason A. Hubbart^b, Michael A. Urban^c

^a School of Natural Resources, University of Missouri, Columbia, MO, 65211, USA

^b West Virginia University, Institute of Water Security and Science, Davis College, Schools of Agriculture and Food, and Natural Resources, Morgantown, West Virginia, 26506, USA

^c College of Arts and Science, Department of Geography, Stewart Hall, Columbia, MO, 65201, USA

ARTICLE INFO

Keywords:

Hydrologic modeling
Urbanization
Climate change
SWAT
Urban growth modeling

ABSTRACT

Future urban development and climatic changes are likely to affect hydrologic regimes in many watersheds. Quantifying potential water regime changes caused by these stressors is therefore crucial for enabling decision makers to develop viable environmental management strategies. This study presents an approach that integrates mid-21st century impervious surface growth estimates derived from the Imperviousness Change Analysis Tool with downscaled climate model projections and a hydrologic model Soil and Water Assessment Tool to characterize potential water regime changes in a mixed-use watershed in central Missouri, USA. Results for the climate change only scenario showed annual streamflow and runoff decreases (−10.7% and −9.2%) and evapotranspiration increases (+6.8%), while results from the urbanization only scenario showed streamflow and runoff increases (+3.8% and +9.3%) and evapotranspiration decreases (−2.4%). Results for the combined impacts scenario suggested that climatic changes could have a larger impact than urbanization on annual streamflow, (overall decrease of −6.1%), and could largely negate surface runoff increases caused by urbanization. For the same scenario, climatic changes exerted a stronger influence on annual evapotranspiration than urbanization (+3.9%). Seasonal results indicated that the relative influences of urbanization and climatic changes vary seasonally. Climatic changes most greatly influenced streamflow and runoff during winter and summer, and evapotranspiration during summer. During some seasons the directional change for hydrologic processes matched for both stressors. This work presented a practicable approach for investigating the relative influences of mid-21st century urbanization and climatic changes on the hydrology of a representative mixed-use watershed, adding to a limited body of research on this topic. This was done using a transferrable approach that can be adapted for watersheds in other regions.

1. Introduction

Land-use and climatic changes are two of the most significant phenomena impacting water regimes globally (Brown et al., 2014; Chung et al., 2011). In terms of land-use change, urban development is second only to agriculture in terms of impairing stream ecosystems (Paul and Meyer, 2001). In many areas throughout the world, rapid spates of urban development have also been accompanied by the buildup of impervious surface (IS) cover, which alters the hydrologic characteristics of watershed landscapes (Kumar et al., 2013; Schueler et al., 2009). The development of these impervious surfaces within watersheds affects the overall hydrologic balance and impacts individual water balance components, often through increased runoff,

reduced evapotranspiration and decreased infiltration (Arnold and Gibbons, 1996; Paul and Meyer, 2001; Redfern et al., 2016; Chen et al., 2017). Relatedly, it has been demonstrated that future urbanization and impervious surface expansion will likely lead to changes in the amount and timing of streamflow, surface runoff and baseflow (Kumar et al., 2013; Sunde et al., 2016; Wu et al., 2015), and result in evapotranspiration (ET) reductions (Kim et al., 2011; Sunde et al., 2016). However, the complexity of the relationship between urban development and water balance processes warrants further investigation into these potential changes, as hydrologic responses to imperviousness differ among various watersheds (Beck et al., 2016; Redfern et al., 2016). While some past research has attempted to help address such issues by linking urban growth projections with hydrologic models in

* Corresponding author. University of Missouri, School of Natural Resources, Department of Forestry, 1111 Rollins St. Room 3, Columbia, MO, 65211, USA.
E-mail address: sundem@missouri.edu (M.G. Sunde).

order to estimate the potential impacts of future urbanization on watershed hydrologic processes (Choi and Deal, 2008; Kumar et al., 2013; Lin et al., 2008; Sunde et al., 2016; Wu et al., 2015), developing a clearer understanding of how hydrologic processes respond to urban development in its various forms remains an important management issue.

Climatic changes, such as increased temperatures and altered precipitation regimes, can also impact watershed hydrologic processes (Arnell and Gosling, 2013; Jiménez-Cisneros et al., 2014). For example, increasingly frequent extreme precipitation events (Pryor et al., 2014; Walsh et al., 2014) during the past century in the Midwestern United States have already contributed to increased surface runoff and streamflow across much of the region (Romero-Lankao et al., 2014; Jiménez-Cisneros et al., 2014; Georgakakos et al., 2014). Climate projections also suggest that both the frequency and magnitude of such events could continually increase over coming decades (Sun et al., 2015; Walsh et al., 2014). Projected changes to the precipitation regime vary directionally by season. In Midwestern states such as Missouri, 21st century climate model projections suggest sizeable precipitation increases during the winter and spring, minor increases during the fall, and decreases during summer (Sun et al., 2015). Temperatures and heat wave occurrences have already increased across the region (Pryor et al., 2014), and climate projections indicate that these will continually increase during the rest of this century (Romero-Lankao et al., 2014; Walsh et al., 2014; Sun et al., 2015). These temperature increases are likely to contribute to increased ET in many areas (Jiménez-Cisneros et al., 2014) and are expected to lead to soil moisture decreases across most of the Midwestern region, most notably during summer (Walsh et al., 2014). Understanding hydrologic responses to these climatic changes is important as these can have implications for water supplies, nutrient loading to receiving bodies, and other critical management issues. Some of these potential changes have been investigated in past studies, where climate model projections have been integrated with hydrologic models to estimate potential climate change effects on water regimes (Cherkauer and Sinha, 2010; Chien et al., 2013; Dams et al., 2015; Ficklin et al., 2009; Jin and Sridhar, 2012; Joh et al., 2011; Mohammed et al., 2015; Ouyang et al., 2015; Sheshukov et al., 2011; Vo et al., 2016; Xu et al., 2013).

The hydrologic responses to climatic changes observed in previous studies were variable, owing largely to differences in the characteristics of the watersheds being analyzed, yet it has been consistently demonstrated that hydrologic processes such as surface runoff, streamflow, baseflow, and ET are likely to be impacted by future climatic changes in most areas (Cherkauer and Sinha, 2010; Dams et al., 2015; Ficklin et al., 2009; Joh et al., 2011; Ouyang et al., 2015; Sunde et al., 2017; Wang et al., 2017; Xu et al., 2013). However, since most areas have experienced land-use changes (e.g. urbanization, deforestation) and climatic changes concurrently, it is often difficult to attribute observed water regime changes to climate change or land cover change alone (Bierwagen et al., 2010; Georgakakos et al., 2014). It has been shown that the relative influence of the two stressors can vary, and that water regime processes respond differently depending on watershed characteristics (Cuo et al., 2011; El-Khoury et al., 2015; Fan and Shibata, 2015; Franczyk and Chang, 2009; Mishra et al., 2010; Neupane and Kumar, 2015; Pervez and Henebry, 2015; Qi et al., 2009; Rahman et al., 2015; Viger et al., 2011). To address this issue, integrated modeling approaches using land-cover change models, climate projections, and hydrologic models have been incorporated into some studies to investigate both the individual and combined hydrologic impacts of climatic and land-use changes. In some instances, studies have indicated that climatic changes can more severely impact water regimes than urbanization and/or land-use changes (Cuo et al., 2011; Fan and Shibata, 2015; Qi et al., 2009; Rahman et al., 2015; Wang et al., 2014; Wilson and Weng, 2011). However, for other areas, it has been demonstrated that land-cover changes could have greater impacts than climatic changes on streamflow processes (Mishra et al., 2010). In

addition, the impacts of climatic and land-cover changes on hydrologic processes can be compounded by one another in some instances (El-Khoury et al., 2015; Franczyk and Chang, 2009; Neupane and Kumar, 2015) and offset by each other in other cases (Viger et al., 2011).

The previously discussed studies have contributed to a growing body of research investigating the impacts of two of the most significant stressors affecting hydrologic regimes globally. However, uncertainty regarding how watersheds in various regions will respond to the combined effects of future climatic and land-cover changes necessitates continued integrated modeling to improve the understanding of their respective influences on hydrologic processes. In urbanizing watersheds, this can be achieved using modeling approaches that utilize fine-scale urban growth projections, downscaled climate projections, and process-based hydrologic models to develop information with application potential for natural resource managers.

Given the preceding background and concerns, the overarching objective of this study was to use an integrated modeling approach to estimate the potential impacts of urbanization and climatic changes in a mixed-use watershed in the Midwestern United States. This approach involved simulating fine-scale future impervious surface growth for the study watershed using a cellular automata based urban growth model, calibrating and validating a process-based hydrologic model for the study watershed, and using downscaled global climate model (GCM) output with the projected impervious surface cover to force a hydrologic model to estimate the relative and combined effects of these stressors on streamflow processes for the study watershed. Specifically, these objectives were achieved by: 1) calibrating and executing the Imperviousness Change Analysis Tool (I-CAT) to simulate pixel level impervious surface cover for the Columbia, Missouri area, 2) conducting sensitivity analysis and parameterization of the Soil and Water Assessment Tool (SWAT) for Hinkson Creek Watershed and 3) using impervious cover derived from I-CAT along with downscaled GCM output from a stochastic weather generator to force SWAT and generate hydrologic estimates.

2. Methods

2.1. Study area

Located in the Midwestern US in central Missouri, Hinkson Creek Watershed (HCW) comprises an area of approximately 231 km² (Fig. 1). Elevations in HCW range from 170 to 290 m (Gesch et al., 2002), and land cover is approximately equal parts urban developed area, forest area, and agricultural (cropland/pasture) lands (Sunde et al., 2016). Karst features, bluffs, and loess-covered uplands are found throughout the central and southeastern portions of HCW, whereas the northwestern areas of the watershed are largely comprised of thin loess soils underlain by glacial till and claypans (Nigh and Schroeder, 2002). Based on its land-cover and economic characteristics, HCW is an emblematic contemporary mixed-use, urbanizing watershed (Hubbart and Zell, 2013). HCW encompasses approximately 60% of Columbia, Missouri, a city which has had large population increases and associated impervious surface development over recent decades (Sunde et al., 2016). From 2000 to 2015 the population of the city increased by over 41%, from approximately 84,000 to over 119,000 (US Census Bureau, 2015). Additionally, while impervious surface area in the watershed increased by just 12.7% from 1980 to 1990, recent urbanization has occurred more rapidly, with increases of 24.1% (1990–2000) and 32.5% (2000–2011) during the following decades (Zhou et al., 2012; Xian et al., 2011). After placement on the impaired waters list under the guidelines of the Clean Water Act in 1998, Hinkson Creek (HC) has been the subject of numerous studies. In some of these studies, researchers have characterized the local impacts of recent urbanization on hydrologic processes, nutrient and sediment yields, and aquatic biota in HCW (Hubbart and Zell, 2013; Kellner and Hubbart, 2016; Nichols et al., 2016; Zeiger and Hubbart, 2016a; b).

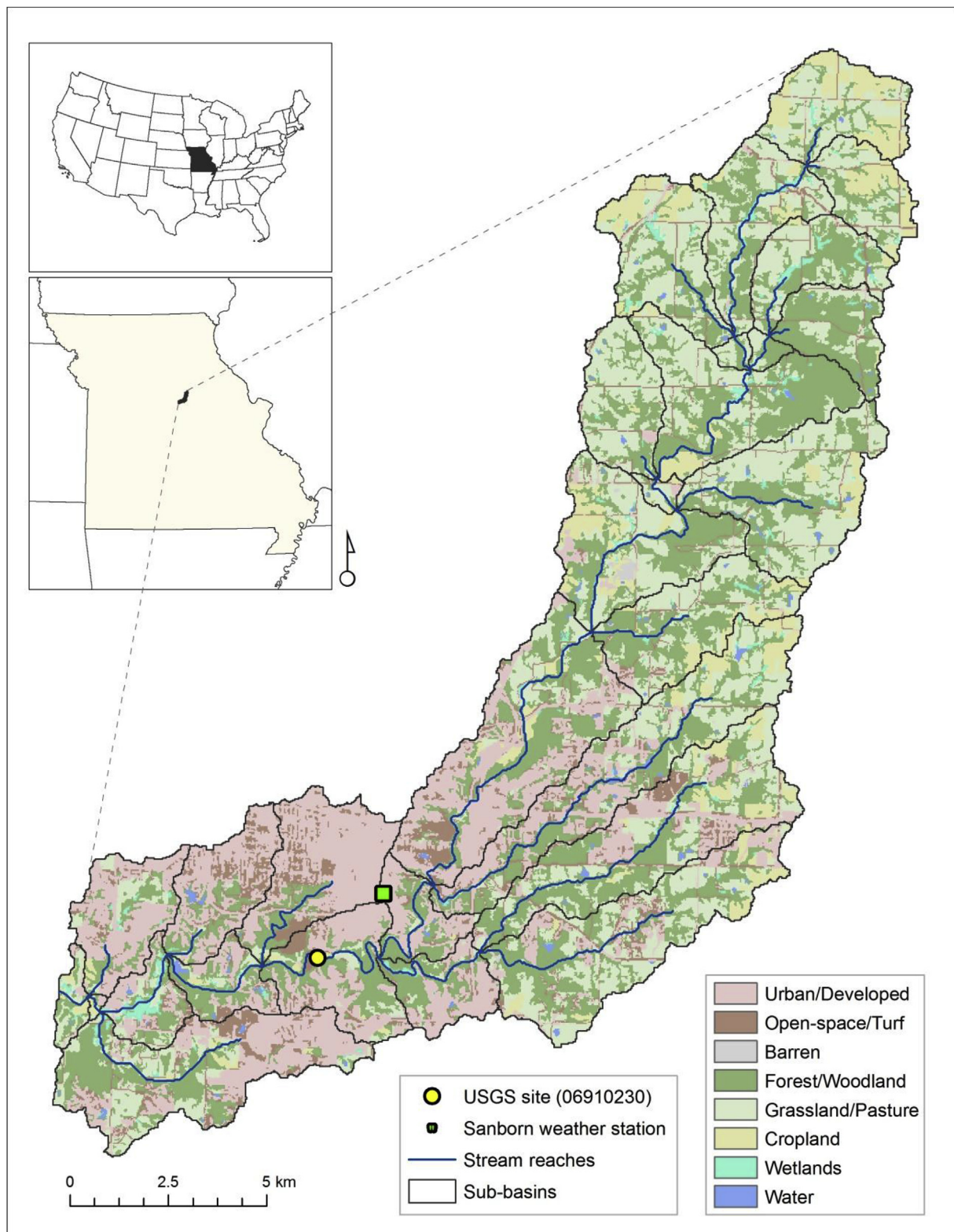


Fig. 1. The study area, Hinkson Creek Watershed (HCW), stream gauge site (USGS 06910230) and weather station (Sanborn Field) used for this analysis. Also shown here are SWAT delineated sub-basins and stream reaches, and generalized NLCD 2011 land cover.

Streamflow observations recorded by a US Geological Survey stream gauge site (USGS 06910230) at HC indicated that the average monthly discharge for the years 2007 to 2017 was $2.31 \text{ m}^3/\text{s}$. The highest average monthly streamflow at HC occurred during spring ($3.94 \text{ m}^3/\text{s}$), whereas the lowest monthly streamflow occurred during winter ($1.37 \text{ m}^3/\text{s}$). Summer and autumn streamflow averages during the same

period were $2.16 \text{ m}^3/\text{s}$ and $1.73 \text{ m}^3/\text{s}$, respectively. Observations from the Sanborn Field weather station (Fig. 1) for 1995–2017 indicated that the average annual precipitation in HCW was $1043 \text{ mm}/\text{yr}$, and that the annual average maximum and minimum temperatures were 18.9°C and 8.1°C , respectively. The patterns observed for seasonal streamflow matched those of seasonal precipitation for HCW. The seasons with the

highest amount of precipitation during the observation period was spring (323 mm) and summer (318 mm), the season with the lowest precipitation was winter (172 mm). The average precipitation depth for fall was 230 mm. On a monthly basis, HCW receives the largest amounts of precipitation during May (132 mm/mo), April (117 mm/mo) and June (114 mm/mo), and receives the lowest amount of precipitation during January (54 mm/mo), December (56 mm/mo) and November (57 mm/mo).

2.2. Hydrologic model (SWAT) description and parameterization

The Soil and Water Assessment Tool (SWAT) was selected for this study because it has been demonstrated that the model can be used to effectively analyze long term climatic and land-cover change impacts for watersheds of various scales and physical characteristics (Gassman et al., 2007; Gassman et al., 2014; Sunde et al., 2016; Zeiger and Hubbard, 2016a). The SWAT is a semi-distributed, physically-based watershed hydrologic model, designed to allow users to determine the effects of various management decisions on water balance components, stream sedimentation, and nutrient loading (Arnold et al., 2012; Gassman et al., 2007). Within the SWAT modeling framework, a watershed is divided into sub-basins, which are then divided into non-spatial units referred to as hydrologic response units, or HRUs. Each HRU represents a proportion of the area of a sub-basin sharing identical land-cover, soil, and slope types. Hydrologic processes are simulated for all HRUs within a sub-basin for each time-step to determine quantities for water balance components such as surface runoff, baseflow and ET, and streamflow is routed sequentially through the sub-basins within the watershed (Arnold et al., 1998; Neitsch et al., 2011). Spatial grids representing land-cover types, soil types, and elevations are required to generate the sub-basins and HRUs used in the SWAT modeling processes. In addition, climatic data for one or more locations within a watershed are required for model forcing. The model is calibrated and validated by comparing simulated streamflow data with observed streamflow for the same watershed over a given time period, generally 3–5 years for each period (Moriassi et al., 2007). Prior to model calibration, a sensitivity analysis is typically performed to identify the parameters that most affect the streamflow values generated by the model, and parameters must be held within physically meaningful ranges (Arnold et al., 2012). Additionally, modeled annual values for processes such as ET and baseflow are often compared with local/regional estimates to ensure that SWAT realistically simulates the

hydrology for a given watershed (Moriassi et al., 2007). Slope and elevation data for this analysis were derived from a USGS 1 arc-second digital elevation model (Gesch et al., 2002, USDA) for the HCW area. A soil grid and the associated soil parameters were generated based on the US Department of Agriculture (USDA) Soil Survey Geographic Database (SSURGO; Soil Survey Staff, 2015) for HCW. The land-cover data used in SWAT was based on the USDA 2011 National Land Cover Dataset (Homer et al., 2015) along with grid-based high resolution IS cover data from a prior Missouri urban growth analysis (Zhou et al., 2012). Meteorological data recorded at the University of Missouri Sanborn Field weather station (Fig. 1) were used to provide model forcing for the SWAT; these included daily maximum and minimum temperature, precipitation, and incident shortwave solar radiation. For this study, a multiple HRU approach was used in SWAT, wherein higher thresholds result in more generalization. The thresholds used to generate the HRUs were: land-use percentage = 0%, soil class percentage = 10%, and slope class percentage = 10%. Under this approach, each sub-basin is divided into areas of unique land-cover types (0% = no land-cover types within a sub-basin are eliminated), soil classes that do not comprise at least 10% within each land-cover area eliminated, and slope classes that do not comprise at least 10% within each soil area are eliminated. This model configuration resulted in the generation of 3060 unique HRUs.

The performance of the model in this study was evaluated through calibration and validation based on observed streamflow from a USGS gauging station at Hinkson Creek (Fig. 1). A group of 24 model input parameters known to influence simulated hydrology was selected based on an array of past SWAT studies and reviews (Ahmadi et al., 2014; Arnold et al., 2012; Cijin et al., 2010; Feyereisen et al., 2007; Holvoet et al., 2005; Jha et al., 2006; Joh et al., 2011; Rossi et al., 2008; White and Chaubey, 2005). The selected group of parameters was then used to conduct a one-at-a-time sensitivity analysis for HCW. Based on the sensitivity analysis, 11 parameters were chosen to calibrate SWAT for streamflow for HC; these included: the runoff curve number (CN2), soil available water capacity (SOL_AWC), shallow aquifer recharge delay time (GW_DELAY), soil bulk density (SOL_BD), maximum leaf area index (BLAI), soil evaporation compensation coefficient (ESCO), plant uptake compensation factor (EPCO), maximum canopy interception (CANMX), and soil layer depth (SOL_Z), effective hydraulic conductivity in main channel alluvium (CH_K2), and threshold water depth in shallow aquifer for return flow (GWQMN). SWAT was calibrated and validated with a commonly used split-sample approach (Moriassi et al.,

Table 1

Calibration ranges and modifications for selected Soil Water and Assessment Tool parameters for Hinkson Creek Watershed.

Parameter	Parameter Range		Initial Calibration Range		Final Calibration Range		Calibration Value
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	
BLAI ^a	0.5	10	−0.5	+0.5	−0.25	+0.01	−0.217
CANMX	0	100	1	25	1	15	7.420
CN2 ^a	25	98	−0.25	+0.25	+0.01	+0.06	+0.057
EPCO	0	1	0.1	1	0.1	0.5	0.272
ESCO	0	1	0.1	1	0.5	1	0.963
SOL_AWC ^a	0	1	−0.25	+0.25	−0.2	+0.05	−0.036
SOL_BD ^a	0.9	2.5	−0.25	+0.25	−0.2	+0.05	−0.002
SOL_Z ^a	0	3500	−0.25	+0.25	−0.2	+0.05	−0.069
CH_K2	−0.01	500	0	20	0	10	0.005
GW_DELAY	0	500	1	30	1	15	1.566
GWQMN	0	5000	1	750	10	200	91.795

Parameter definitions: **BLAI**: Maximum leaf area index; **CANMX**: maximum canopy storage; **CN2**: SCS runoff curve number; **EPCO**: plant uptake compensation factor; **ESCO**: soil evaporation compensation coefficient; **SOL_AWC**: soil available water capacity; **SOL_BD**: soil bulk density; **SOL_Z**: soil layer depth; **CH_K2**: effective hydraulic conductivity in main channel alluvium; **GW_DELAY**: Groundwater delay time (days); **GWQMN**: threshold water depth in shallow aquifer for return flow.

^a Spatially distributed parameters were adjusted using relative changes based on the calibration value (e.g. $CN2_{New} = CN2_{Old} + CN2_{Old} * Calibration_Value$). Other parameters adjusted using replace method.

2012) that involves dividing observed streamflow data into two time periods (i.e. calibration and validation). Accordingly, the observed streamflow record from the USGS site for April 2007–December 2017 was split into calibration (April 2007–December 2012; 69 months) and validation periods (January 2013–December 2017; 60 months). After constraining the initial parameter ranges within realistic limits (Table 1), the SWAT Calibration and Uncertainty Procedures (SWAT-CUP) interface (Abbaspour et al., 2007; Arnold et al., 2012) was used to modify parameter values until the model produced reliable hydrologic estimates. In addition to streamflow, the reliability of model estimated ET values was verified through comparisons between the modeled yearly average using current climate data (approximately 61 cm/year) and the historical average, approximately 60–69 cm/year (Galat et al., 2005; Sanford and Selnick, 2013). These comparisons suggested that the model, as parameterized for this study, was capable of producing very realistic ET estimates. Similarly, model simulated yearly average baseflow (~14% of total flow) was judged to be very realistic based on comparisons with previously mapped baseflow (Wolock, 2003) and past research in HCW (Hubbart and Zell, 2013; Wei et al., 2018). A monthly time-step was used to generate streamflow estimates with the SWAT, and model performance was evaluated using the Nash-Sutcliffe efficiency (NSE), the coefficient of determination (R^2), and percent bias (PBIAS) which are commonly used indices for assessing hydrologic model performance (Moriassi et al., 2007, 2015). The respective R^2 , NSE and PBIAS values for modeled streamflow during the calibration and validation periods were 0.88, 0.84 and 6.4%, and 0.80, 0.78 and 12.6% (Fig. 2). According to recently published guidelines (Moriassi et al., 2015), the calibration period values were ‘very good’ (R^2), ‘very good’ (NSE), and ‘good’ (PBIAS), and the validation period values were ‘good’ (R^2), ‘good’ (NSE), and ‘satisfactory’ (PBIAS). In addition, these updated guidelines are more stringent than the widely used guidelines presented by Moriassi et al. (2007). Both cases indicate that the model configuration presented here was effective for hydrologic simulations in HCW.

2.3. Urban growth model (I-CAT) description and parameterization

The Imperviousness Change Analysis Tool (I-CAT) was chosen to simulate urban growth for this study because it can be used to generate

high resolution impervious surface estimates for a wide variety of study areas (Sunde et al., 2014). I-CAT is a rule based urban growth model that generates pixel-level impervious surface estimates using multi-criteria evaluation (Carver, 1991) of various explanatory variables, such as slope, distance to road networks, and distance to previous urban development. Within the modeling framework, model users have the ability to incorporate additional modeling elements, including spatial growth constraints and expanded sets of explanatory urban growth variables. A trial and error approach is used to manually calibrate I-CAT. This approach consists of adjusting urban growth parameter weights in order to produce a suitability grid that complements observed urban development grids during the model calibration and validation periods. Given acceptable calibration and validation statistics, the model is then used to project developed pixels for a future year, specified by the model user. Under the I-CAT modeling framework, an array of pixels is generated and each pixel is assigned a percentage impervious surface (PIS) value ranging from 30% to 100%.

For this study, three PIS grids (1900, 2000 and 2011) were used to develop gridded urban growth datasets for two time intervals (i.e. calibration and validation) for the Columbia, Missouri urban area. Observed IS cover for the study area for these two intervals (1990–2000 and 2000–2011) was based on mapped impervious surface from a recent analysis of urban cover in Missouri (Zhou et al., 2012) and US Department of Agriculture National Land Cover Dataset (USDA NLCD) impervious surface cover classifications (Xian et al., 2011). The urban growth drivers used for this analysis included: distance to roads, distance to water bodies, slope, elevation, distance to primary and secondary urban centroids, and distance to primary and secondary urban boundaries. Missouri Department of Transportation (MoDOT, 2010) road network data were used to produce a road network grid for the study area. Grids for slope and elevation were both derived from the 1 arc-second resolution USGS digital elevation model (Gesch et al., 2002). A grid representing water bodies within the modeling domain was derived using USGS National Hydrography Dataset (USGS, 1999) vectors in combination with water features from the USDA NLCD 2011 (Homer et al., 2015). All spatial grids were sampled at a 30 m resolution in order to maintain consistency across the datasets and models used for this study. The calibration process for I-CAT for the Columbia, Missouri area indicated that the slope percentage and the distance to secondary

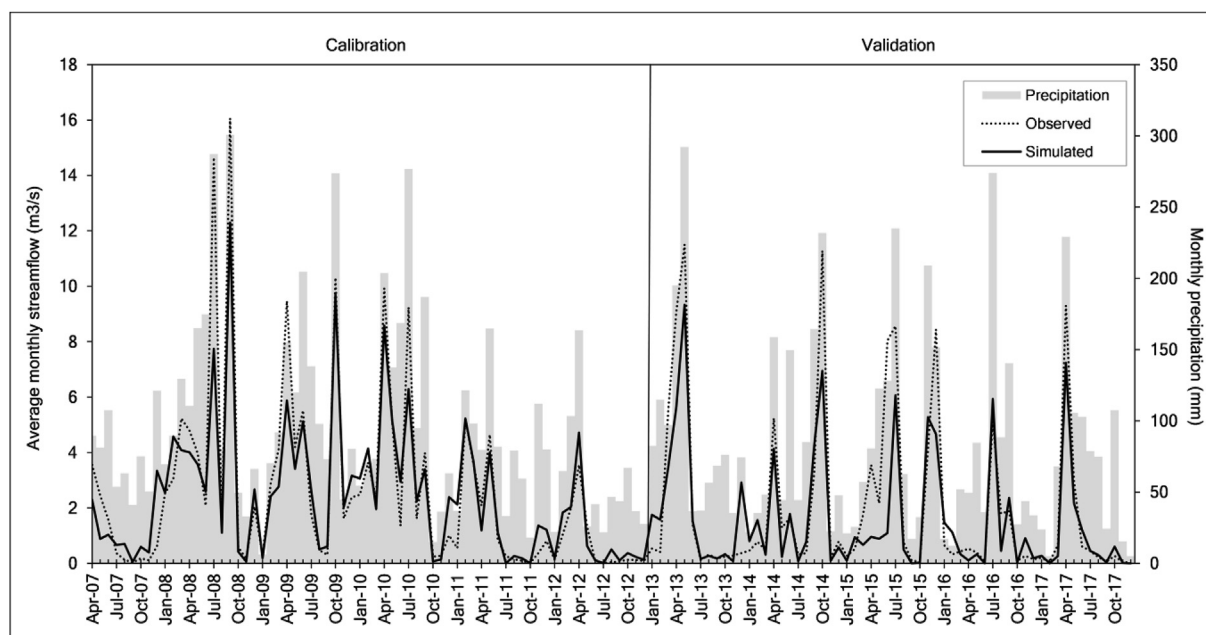


Fig. 2. Simulated and observed stream discharge for Hinkson Creek, along with observed precipitation for the study calibration and validation periods.

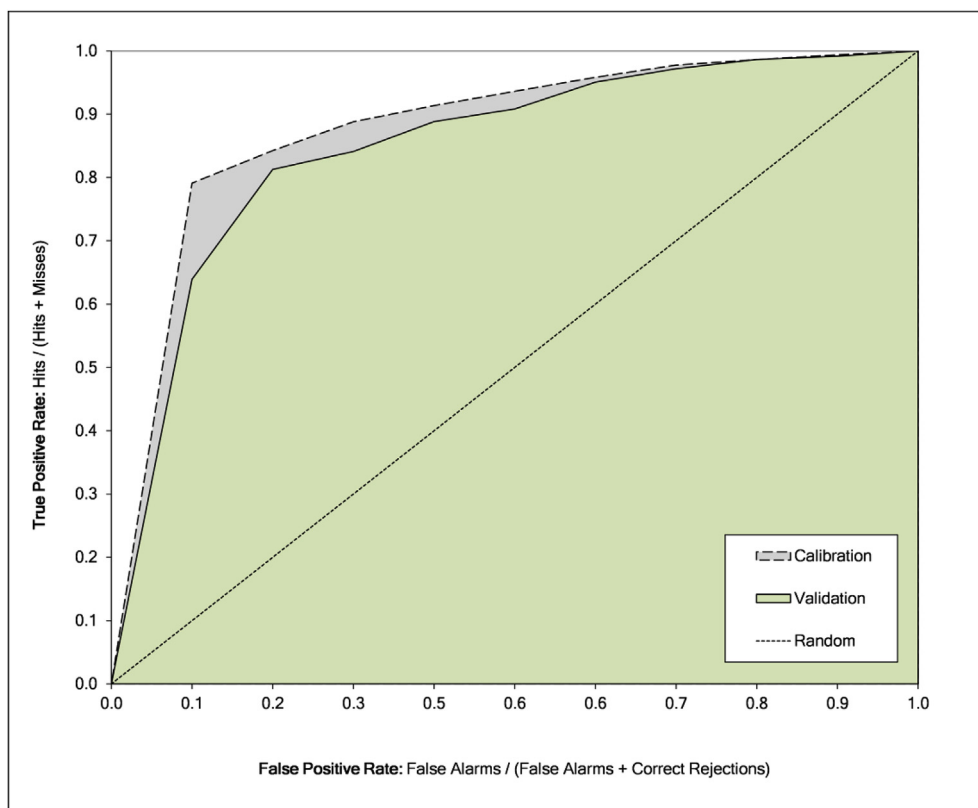


Fig. 3. Area under the curve. (AUC) for impervious surface development simulated using the Imperviousness Change Analysis Tool (I-CAT) for the calibration (1990–2000) and validation (2000–2011) periods.

urban boundaries were the most influential urban growth determinants used in this study.

The performance of the model for the calibration and validation periods was quantified by analyzing the relative operating characteristic (ROC) statistic for each period, a commonly used approach for evaluating the effectiveness of land-cover change models (Pontius and Schneider, 2001). Using the ROC approach, a grid of actual land-cover change events is mapped and intersected with a suitability grid for the same time period, and the spatial coincidence of the two are then assessed (Mas et al., 2013). The resultant metric is the area under curve (AUC) value, where 0.5 indicates randomness, 1.0 indicates a suitability map that describes locations of change extremely well, and 0.0 indicates a suitability map that describes locations without change. The ROC analysis indicated that I-CAT was effective for spatially allocating projected impervious surface growth, yielding AUC values of $AUC = 0.76$ and $AUC = 0.73$ for the calibration and validation periods, respectively (Fig. 3).

2.4. Stochastic weather generator (MarkSim) and climate scenarios

Climate projections used in hydrologic impact assessments are typically based on output from General Circulation Models (GCMs) used in the Coupled Model Intercomparison Projects (e.g. CMIP3/CMIP5). These projections are often downscaled when being used as forcing for hydrologic models, as the GCMs used in these projects typically simulate physical processes at horizontal grid resolutions of approximately $1\text{--}2^\circ$ (Flato et al., 2013; Xu, 1999; Jiménez-Cisneros et al., 2014). By incorporating these downscaled climate projections with hydrologic models, practitioners can estimate climate change impacts on water resources for specific watersheds. For this study, the MarkSim stochastic weather generator (Jones and Thornton, 2013) was used to produce downscaled daily climate data for the study watershed. In

addition to being capable of generating data that accurately represents historical climate, the MarkSim model also allows users to apply ensemble GCM projections to stochastically generated data (ILRI, 2014; CIAT, CCAFS, 2014). Within MarkSim, climate data for given a latitude, longitude, and elevation are used to produce model parameters describing local climate. These parameters are used in the model algorithms to generate daily precipitation, air temperature and solar radiation data, and can be linked to GCM differential values to produce downscaled time series data that can be linked with hydrologic models (Jones and Thornton, 2013).

To characterize mid-21st century climate for HCW in this study, an ensemble of seventeen GCMs from the CMIP5 (Appendix A) was applied during the weather generation execution to produce 30 years of climate data around the year 2060 under the RCP8.5 emissions scenario (Riahi et al., 2011; vanVuuren et al., 2011; Cubasch et al., 2013). Daily precipitation, maximum and minimum temperature, and incident short-wave solar radiation data from the Sanborn Field weather station (Fig. 1) for the period from January 1st, 1997–December 31st, 2017 were used to characterize the current climate of HCW. In order to generate a current climate dataset comparable to the 30 years of generated mid-21st century climate data, the time period from January 1st, 2006–December 31st, 2014 was repeated; this allowed the hydrologic model to be run for matching time periods.

3. Results and discussion

Seasonal comparisons for precipitation and temperature (Table 2) for the two climate scenarios, current climate and mid-21st century climate, indicated that the most notable potential changes under climate change could be decreases to winter precipitation (-18.2%), increases to summer precipitation ($+7.6\%$), and large increases to seasonal temperature maxima and minima, particularly during winter and

Table 2

Climate comparisons for Hinkson Creek Watershed, including projected temperature and precipitation departures from current climate under the mid-21st century climate scenario (changes expressed in mm/H₂O and percentage change).

	Precip. (mm)		Change	
	Current	Mid-Century	Mid-Century	Mid-Century
Winter	181	148	−33.0	−18.2%
Spring	327	352	25.0	7.6%
Summer	319	310	−9.0	−2.8%
Fall	245	251	6.0	2.4%
Annual	1072	1061	−11.0	−1.0%
	Max. (°C)		Change	
	Current	Mid-Century	Mid-Century	Mid-Century
Winter	5.6	7.7	2.1	37.5%
Spring	19.3	21.2	1.9	9.8%
Summer	30.6	34.3	3.7	12.1%
Fall	20.1	23.3	3.2	15.9%
Annual	18.9	21.6	2.7	14.4%
	Min. (°C)		Change	
	Current	Mid-Century	Mid-Century	Mid-Century
Winter	−4.1	−2.5	1.6	39.0%
Spring	8.0	8.9	0.9	11.3%
Summer	19.7	21.7	2.0	10.2%
Fall	8.8	10.7	1.9	21.6%
Annual	8.1	9.7	1.6	19.8%

fall. In order to characterize the potential mid-21st century urban land-cover in HCW, future impervious surface cover under a current trend growth scenario was projected from 2011 to 2051 using the previously described I-CAT model configuration. The resultant 2051 impervious cover grid (Fig. 4) was then used to define urban land-cover for the future urbanization scenario for the SWAT simulations. The climatic and land-cover data described above were used as forcing for the SWAT in order to compare the potential effects of both future urbanization and climatic changes in HCW. Identical climate data for all of the scenarios were used to force SWAT for a warm-up period (1/1/2007–12/31/2016) to enable the model to equilibrate hydrologically. The model was subsequently run for each of the four scenarios described below. The four scenarios developed for this study were: 1) a baseline scenario (current) based on current land-cover and climate, 2) a climate change only scenario (Δ_{CC}) based on current land-cover and mid-century climate projections, 3) a mid-century urbanization with current climate scenario (Δ_U) based on simulated mid-century imperviousness and current climate, and 4) a mid-century urbanization with climate change scenario (Δ_{UC}) based on mid-century imperviousness and climate change projections.

Model results derived from the SWAT for the four scenarios (current, Δ_{CC} , Δ_U , and Δ_{UC}) scenarios were compared in order to determine the potential effects of future urbanization and climatic changes in HCW. Simulation results at the annual level (Fig. 5) for total flow indicated that climatic changes could potentially be more influential than urbanization in HCW, as flow increases caused by urbanization were not sufficient to offset climate influenced decreases. Relative to the baseline scenario, streamflow could decrease under the Δ_{CC} (−10.7%)

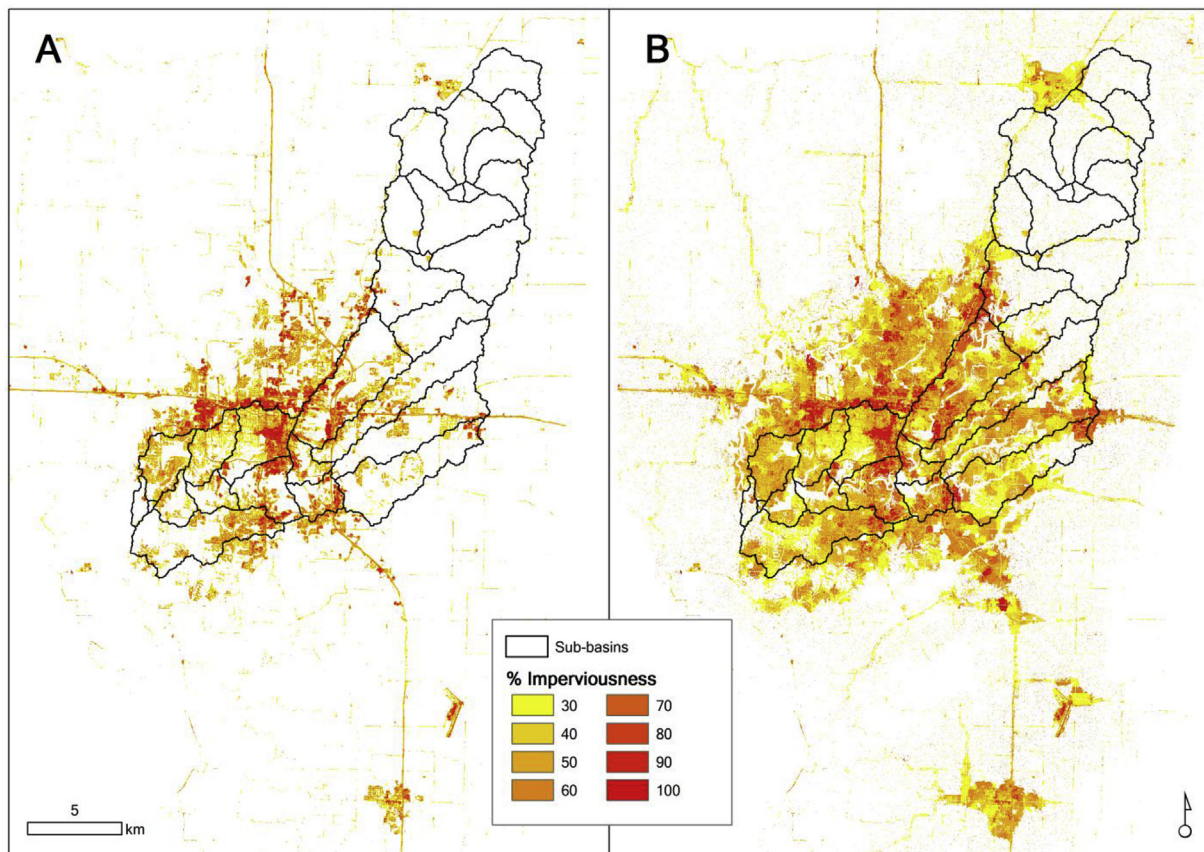


Fig. 4. Baseline (2011) percentage impervious surface coverage for the Columbia, Missouri urban area (A), along projected mid-21st century coverage (2051) modeled with I-CAT (B).

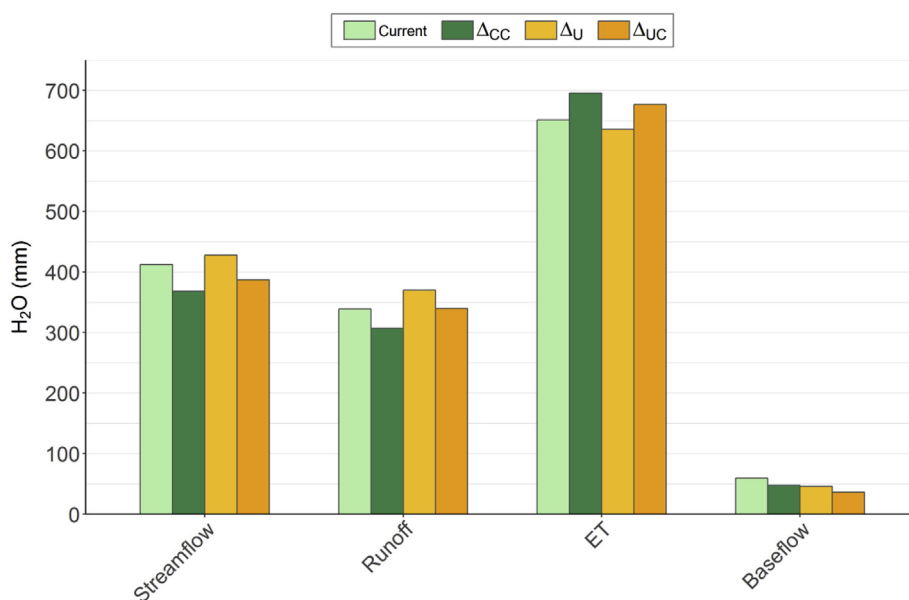


Fig. 5. Comparison of modeled annual average values for water balance components for Hinkson Creek Watershed under the four scenarios (current, Δ_{CC} , Δ_U , and Δ_{UC}).

Table 3

Simulated average annual values for water balance components for Hinkson Creek Watershed for the climate scenarios, including estimated changes (mm/ H_2O and percentage change) relative to baseline conditions.

Variable	H_2O (mm)				Percent Change		
	Current	Δ_{CC}	Δ_U	Δ_{UC}	Δ_{CC}	Δ_U	Δ_{UC}
Streamflow	412	368	428	387	−10.7%	+3.9%	−6.1%
Runoff	339	307	370	340	−9.4%	+9.1%	+0.3%
ET	651	696	635	677	+6.9%	−2.5%	+4.0%
Baseflow	60	48	46	36	−20.0%	−23.3%	−40.0%

scenario, increase under the Δ_U (+3.8%) and decrease Δ_{UC} (−6.1%) scenarios (Table 3). In terms of annual surface runoff, the influences of the two factors largely offset each other. Surface runoff decreased under the Δ_{CC} scenario (−9.2%) and increased under Δ_U (+9.3%), while the Δ_{UC} (+0.3%) scenario yielded a marginal increase (Table 3). Climatic changes also exerted a greater influence on annual ET than urbanization; an overall increase was observed when both factors were considered. Results showed overall increases to annual ET under Δ_{CC} (+6.8%), decreases under the Δ_U (−2.4%) scenario and increases under the Δ_{UC} (+3.9%) scenario. ET decreases observed under the urbanization scenario were likely the consequence of the replacement of forested areas, woodlands, croplands and pastures with developed urban areas (Sunde et al., 2016), which resulted in reduced canopy cover, routing water as runoff that would have otherwise been consumed or intercepted by plants (Neitsch et al., 2011). Climatic changes and urbanization both tended to influence baseflow in same direction, with decreases observed under all cases. In ascending order, annual baseflow decreases were observed for the Δ_{CC} , the Δ_U , and the Δ_{UC} scenarios (Table 3).

The responses of water regime processes in HCW to projected climatic changes and urbanization varied according to season (Fig. 6). The largest changes to mean fall streamflow occurred under the Δ_{CC} scenario (−10.1%) and Δ_U scenario (+9.1%). However, when both factors were considered simultaneously, fall streamflow increased (Table 4). Directional changes to average spring flow were the same for both stressors, with climatic changes exerting a greater influence relative to

urbanization. Changes to average flow during spring were greatest under Δ_{CC} (+12.0%) and Δ_{UC} (+13.9%). During summer and winter the largest streamflow changes occurred when climatic changes were considered, with large decreases under Δ_{CC} (−39.3%, −20.5%) and Δ_{UC} (−31.9%, −21.2%) for both seasons. While there were urbanization influenced increases during these seasons, the results indicated these were negated when considering both factors. The responses of surface runoff to the two stressors largely matched those observed for overall flow, with the exception of a notable increase to fall runoff when considering both urbanization and climatic changes. Average fall surface runoff increased under the Δ_U (+13.3%) and Δ_{UC} (+9.8%) scenarios and decreased (−7.3%) during the same season under Δ_{CC} . During spring, surface runoff increased under all three scenarios (Δ_{CC} = +20.8%, Δ_U = +8.1%, Δ_{UC} = +28.6%). While there were large decreases to runoff during the summer and winter under the Δ_{CC} (−39.8%, −27.4%) and Δ_{UC} (−27.6%, −23.7%) scenarios, urbanization alone resulted in increases for the two seasons (+13.4%, +4.0%). The seasonal response of ET was generally opposite when considering each of the stressors; with the exception of fall under the Δ_{CC} scenario, seasonal ET increased in response to climatic change and decreased in response to urbanization. Additionally, the influence of climate on ET was generally more intense than that of urbanization. Decreases to ET were observed under all of the scenarios during fall (Δ_{CC} = −1.2%, Δ_U = −5.0%, Δ_{UC} = −8.0%). Spring, summer and winter ET increased under the Δ_{CC} (+5.4%, +11.6%, +3.1%) and Δ_{UC} (+3.8%, +9.0%, +3.4%) and decreased marginally for the same seasons under the Δ_U scenario (−1.8%, −1.9%, −1.1%). With the exception of winter under the Δ_{CC} scenario, baseflow decreased for all season/scenario combinations (Table 4). It is possible that the lone observed baseflow increase occurred as a result of a decoupling of the balancing effect between ET, precipitation and baseflow that takes place during cold seasons in many areas, which can lead to such increases (Ficklin et al., 2016), or simply as a result of an average increase of precipitation during spring under Δ_{CC} .

Seasonal interquartile ranges (IQR) were determined in order to evaluate the variability of water process estimates under each of the scenarios for HCW (Fig. 7). The modeling results suggested that the variability of streamflow responses in HCW could decrease during the winter, spring, and summer under the scenarios that included climatic

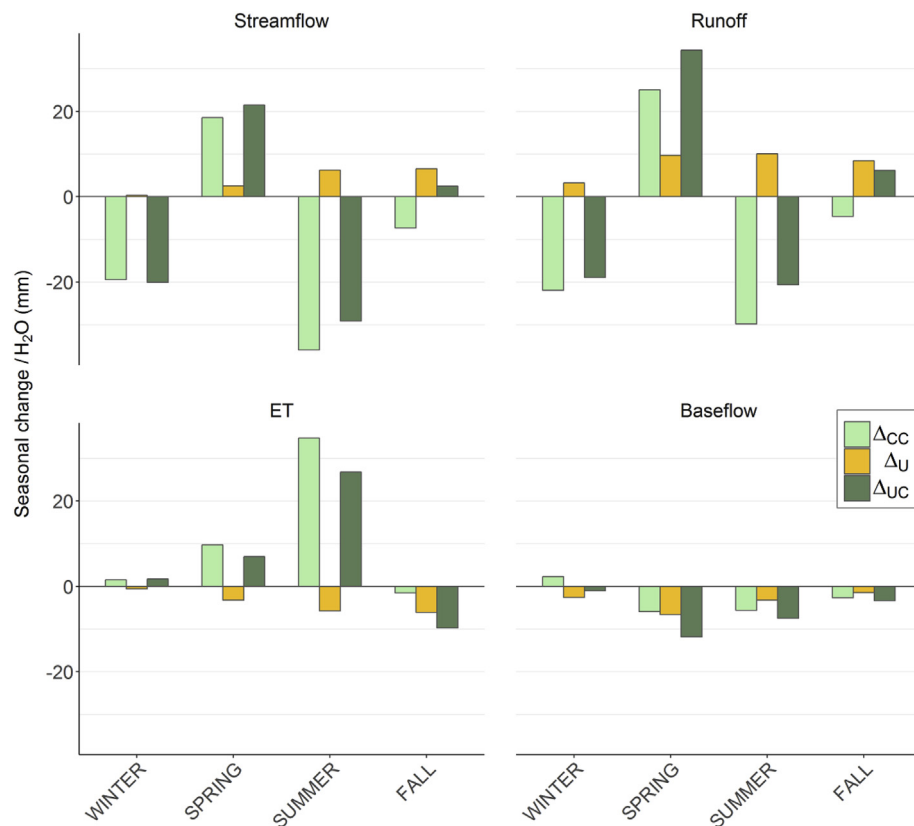


Fig. 6. Comparison of modeled average seasonal departures from current climate scenario for components of water balance in Hinkson Creek Watershed under the three potential change scenarios (Δ_{CC} , Δ_U , and Δ_{UC}).

Table 4

Seasonal changes (mm/H₂O) and percentage changes to water balance variables in Hinkson Creek Watershed for the Δ_{CC} , Δ_U , and Δ_{UC} scenarios.

Streamflow Δ_{CC}			Streamflow Δ_U		Streamflow Δ_{UC}	
Winter	-19	-20.5%	0	0.4%	-20	-21.2%
Spring	19	12.0%	3	1.6%	22	13.9%
Summer	-36	-39.3%	6	6.9%	-29	-31.9%
Fall	-7	-10.1%	7	9.1%	3	3.4%
Runoff Δ_{CC}			Runoff Δ_U		Runoff Δ_{UC}	
Winter	-22	-27.4%	3	4.0%	-19	-23.7%
Spring	25	20.8%	10	8.1%	34	28.6%
Summer	-30	-39.8%	10	13.4%	-21	-27.6%
Fall	-5	-7.3%	8	13.3%	6	9.8%
ET Δ_{CC}			ET Δ_U		ET Δ_{UC}	
Winter	2	3.1%	-1	-1.1%	2	3.4%
Spring	10	5.4%	-3	-1.8%	7	3.8%
Summer	35	11.6%	-6	-1.9%	27	9.0%
Fall	-2	-1.2%	-6	-5.0%	-10	-8.0%
Baseflow Δ_{CC}			Baseflow Δ_U		Baseflow Δ_{UC}	
Winter	2	19.0%	-3	-21.4%	-1	-8.5%
Spring	-6	-20.0%	-7	-22.4%	-12	-39.8%
Summer	-6	-44.3%	-3	-25.6%	-8	-59.2%
Fall	-3	-48.6%	-2	-27.0%	-3	-61.3%

changes (Fig. 8). For spring and fall streamflow, variability held relatively constant among all of the scenarios, ranging from 107 mm (Δ_{UC}) to 114 m (current) during spring, and from 52 mm (Δ_{CC}) to 55 (Δ_{UC})

during fall. Relative to the baseline scenario, the variability of summer and winter streamflow was reduced under Δ_{CC} (summer: -30 mm, winter: -27 mm) and Δ_{UC} (summer: -30 mm, winter -28 mm). In terms of surface runoff, the most notable changes were decreased variability during summer and winter under both of the scenarios in which climatic change was considered. The variability of seasonal ET responses was primarily dependent on the specific season and climate scenario. Winter ET variability was not significantly altered under any of the scenarios, and only minor increases were observed during summer for all scenarios. The results showed potential large changes to ET variability during certain seasons for scenarios including a climate change component, with projected increases during spring and fall for Δ_{CC} (spring: +17 mm, fall: +18 mm) and Δ_{UC} (spring: +17 mm, fall: +16 mm). For baseflow, variability decreases were observed during fall and summer under the Δ_{CC} (fall: -6 mm, summer: -9 mm) and Δ_{UC} (fall: -7 mm, summer: -11 mm) scenarios. The baseflow responses for variability were somewhat more varied among the scenarios during spring and winter. During spring, relatively large decreases in variability were observed for Δ_{CC} and Δ_{UC} , and a moderate decrease was observed for the same season under Δ_U . In addition, during winter, increased variability was observed for Δ_{CC} , a moderate decrease was observed under Δ_U , and variability remained similar to that of the baseline scenario under Δ_{UC} .

4. Conclusions

This study presented an integrated modeling approach for assessing the individual and combined effects of urbanization and climatic changes on hydrologic processes in a mixed-use watershed. The

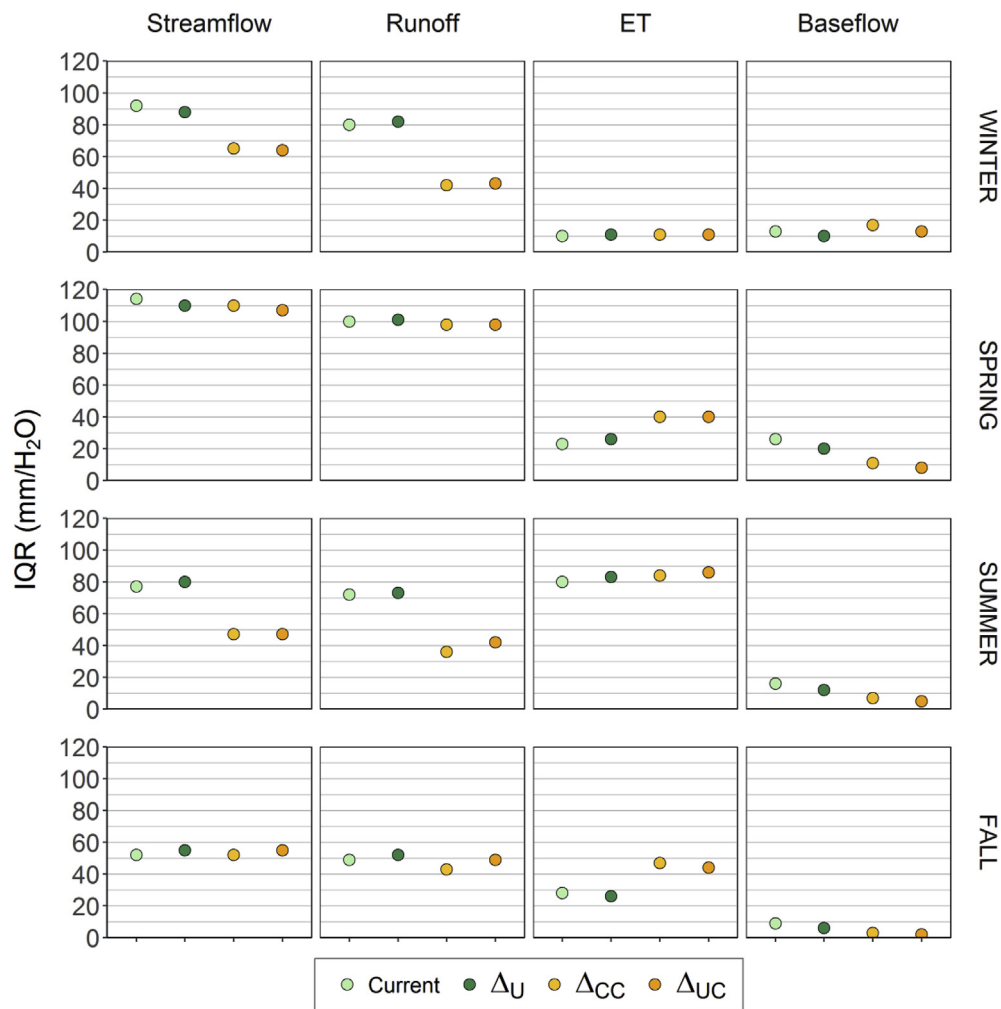


Fig. 7. Cross comparison of interquartile ranges arranged by modeled water balance component and season for the study watershed under each of the four scenarios (current, ΔU , ΔCC , and ΔUC).

approach used a stochastic weather generator (MarkSim) to downscale GCM output from the latest generation of climate models (CMIP5), impervious surface growth projections derived from a CA-based urban growth model (I-CAT), and a process-based watershed hydrologic model (SWAT). Within this modeling framework, three urbanization and climate scenarios were developed and used as input for SWAT to determine the relative impacts of the two stressors. The study results suggested that, at the annual time scale, climatic changes could have a larger impact than urbanization on streamflow offsetting increases caused by urbanization and leading to overall decreases. Climate changes, however, did not dominate the streamflow response during all seasons. During winter, spring and summer climate exerted a greater influence than urbanization on modeled flow, but the impacts of urbanization were most influential during fall. Moreover, during spring, the influence of the two stressors did not vary directionally, as increases were projected for that season under all scenarios. While the modeling results showed that annual and seasonal surface runoff responses under the scenarios largely matched those observed for streamflow, neither stressor was dominant at the annual level. This is reflected in the outcome for the combined effects scenario for surface runoff (< 1%

projected annual increase). Our analysis also indicated that mid-21st climatic changes could affect annual ET more acutely than urbanization. The ET reductions seen under the urban growth scenario were totally offset by climate induced increases, and the combined impacts scenario showed an overall annual increase to ET. Similarly, climatic changes had a greater impact on seasonal ET for every season other than fall, during which urbanization induced decreases dominated the response. This was particularly the case during summer, where large overall ET increases were observed. The results presented in this study underscore the importance of seasonality when considering the combined impacts of future land-cover and climatic changes on hydrologic processes, as the relative importance of either stressor can vary by season. This study also presented a unique approach for assessing the hydrologic impacts of urbanization and climatic change that can be adopted for investigations into potential hydrologic balance alterations in other watersheds. In addition, results from our study characterize potential mid-21st century conditions for the study watershed under multiple scenarios and add to the limited body of research in this area, which can also be useful for researchers and managers studying similar watersheds in the region.

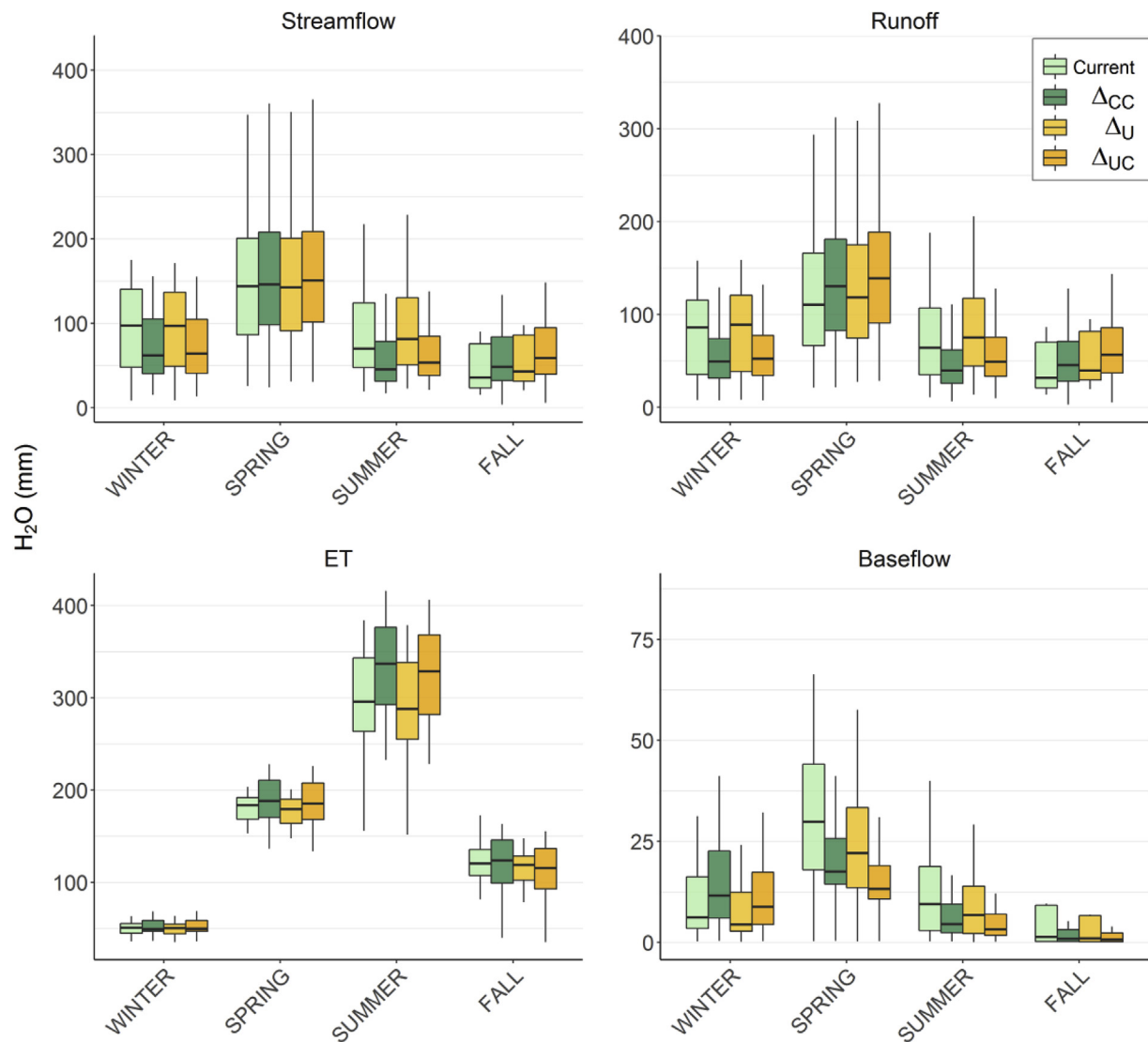


Fig. 8. Comparison of modeled average seasonal variability for water balance components in Hinkson Creek Watershed under all four scenarios (current, Δ_{CC} , Δ_U , and Δ_{UC}).

Acknowledgements

The authors would like to acknowledge the generosity of the

Missouri Department of Conservation and the University of Missouri GIS Mission Enhancement Program for providing funding for the research presented in this paper.

Appendix A. Global Circulation Models incorporated in the MarkSim stochastic weather generator.

Model	Institution	Resolution, Lat x Long φ	Reference
BCC-CSM 1.1/BCC-CSM 1.1(m)	Beijing Climate Centre, China Meteorological Administration	2.8125×2.8125	Wu T (2012). A Mass-Flux Cumulus Parameterization Scheme for Largescale Models: Description and Test with Observations. <i>Clim. Dynam.</i> 38, 725–744
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation and the Queensland Climate Change Centre of Excellence	1.875×1.875	Collier MA et al. (2011) The CSIROmk3.6.0 Atmosphere-Ocean GCM: participation in CMIP5 and data publication. MODSIM 2011, Perth, 12–16 December 2011
FIO-ESM	The First Institute of Oceanography, SOA, China	2.812×2.812	Song Z, Qiao F, Song Y (2012). Response of the equatorial basin-wide SST to wave mixing in a climate model: An amendment to tropical bias, <i>J. Geophys. Res.</i> , 117, C00J26

GFDL-CM3	Geophysical Fluid Dynamics Laboratory	2.0 × 2.5	Donner LJ et al. (2011). The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL Global Coupled Model CM3. <i>Journal of Climate</i> , 24(13).
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory	2.0 × 2.5	Dunne JP et al. (2012). GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models. Part I: Physical Formulation and Baseline Simulation Characteristics. <i>J. Climate</i> , 25, 6646–6665.
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory	2.0 × 2.5	Dunne JP et al. (2012). GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models. Part I: Physical Formulation and Baseline Simulation Characteristics. <i>J. Climate</i> , 25, 6646–6665.
GISS-E2-H/GISS-E2-R	NASA Goddard Institute for Space Studies	2.0 × 2.5	Schmidt GA et al. (2006). Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data. <i>J. Climate</i> 19, 153–192.
HadGEM2-ES	Met Office Hadley Centre	1.2414 × 1.875	Collins WJ et al. (2011). Development and evaluation of an Earth-System model-HadGEM2. <i>GMD</i> 4(4):1051–1075.
IPSL-CM5A-LR/IPSL-CM5A-MR	Institut Pierre-Simon Laplace	1.875 × 3.75/ 1.2587 × 2.5	Dufresne JL et al. (2013). Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. <i>Climate Dynamics</i> , 1–43.
MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	2.8125 × 2.8125	Watanabe S et al. (2011). MIROC-ESM2010: model description and basic results of CMIP5-20c3m experiments. <i>Geoscientific Model Development</i> 4 (4), 845–872.
MIROC-ESM-CHEM/ MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	2.8125 × 2.8125/ 1.4063 × 1.4063	Watanabe S et al. (2011). MIROC-ESM2010: model description and basic results of CMIP5-20c3m experiments. <i>Geoscientific Model Development</i> 4 (4), 845–872.
MRI-CGCM3	Meteorological Research Institute	1.125 × 1.125	Yukimoto S (2012). A new global climate model of Meteorological Research Institute: MRI-CGCM3 – Model description and basic performance. <i>J. Meteorol. Soc. Jpn.</i> , 90a, 23–64
NorESM1-M	Norwegian Climate Centre	1.875 × 2.5	Kirkevåg A, Iversen T, Seland O, Debernard JB, Storelvmo T, Kristjansson JE (2008) Aerosol-cloud-climate interactions in the climate model CAM-Oslo. <i>Tellus A</i> 60(3):492–512. Seland O, Iversen T, Kirkevåg A, Storelvmo T (2008). Aerosol-climate interactions in the CAM-Oslo atmospheric GCM and investigation of associated basic shortcomings. <i>Tellus A</i> 60(3):459–491.

References

- Abbaspour, K.C., Vejdani, M., Haghighat, S., 2007. SWAT-cup calibration and uncertainty programs for SWAT. In: *MODSIM 2007 International Congress on Modelling and Simulation*.
- Ahmadi, M., Arabi, M., Ascough, J.C., Fontane, D.G., Engel, B.A., 2014. Toward improved calibration of watershed models: multisite multiobjective measures of information. *Environ. Model. Softw.* 59, 135–145. <http://dx.doi.org/10.1016/j.envsoft.2014.05.012>.
- Arnell, Nigel W., Gosling, Simon N., April 12, 2013. The impacts of climate change on river flow regimes at the global scale. *J. Hydrology* 486, 351–364. <http://dx.doi.org/10.1016/j.jhydrol.2013.02.010>.
- Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., et al., 2012. SWAT: model use, calibration, and validation. *Trans. ASABE* 55 (4), 1491–1508.
- Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment Part I: model development. *J. Am. Water Resour. Assoc.* 34 (1), 73–89.
- Arnold Jr., C.L., Gibbons, C.J., 1996. Impervious surface coverage: the emergence of a key environmental indicator. *J. Am. Plan. Assoc.* 62 (2), 243–258.
- Beck, Scott M., McHale, Melissa R., Hess, George R., July 1, 2016. Beyond impervious: urban land-cover pattern variation and implications for watershed management. *Environ. Manag.* 58 (1), 15–30. <http://dx.doi.org/10.1007/s00267-016-0700-8>.
- Bierwagen, Britta G., Theobald, David M., Pyke, Christopher R., Choate, Anne, Groth, Philip, Thomas, John V., Morefield, Philip, December 7, 2010. National housing and impervious surface scenarios for integrated climate impact assessments. *Proc. Natl. Acad. Sci.* 107 (49). <http://dx.doi.org/10.1073/pnas.1002096107>. 20887–92.
- Brown, D.G., Polsky, C., Bolstad, P., Brody, S.D., Hulse, D., Kroh, R., Loveland, T.R., Thomson, A., 2014. Chapter 13: Land Use and Land Cover Change. *Climate Change Impacts in the United States: the Third National Climate Assessment*. *Climate Change Impacts in the United States: The Third National Climate Assessment*, pp. 318–332. <http://dx.doi.org/10.7930/J05Q4T1Q>.
- Carver, S.J., 1991. Integrating multi-criteria evaluation with geographical information systems. *Int. J. Geogr. Inf. Syst.* 5 (3), 321–339. <http://dx.doi.org/10.1080/02693799108927858>.
- Chen, Jingqiu, Lawrence, Theller, Gitau, Margaret W., Engel, Bernard A., Harbor, Jonathan M., February 1, 2017. Urbanization impacts on surface runoff of the contiguous United States. *J. Environ. Manag.* 187, 470–481. <http://dx.doi.org/10.1016/j.jenvman.2016.11.017>.
- Cherkauer, K.A., Sinha, T., 2010. Hydrologic impacts of projected future climate change in the lake Michigan region. *J. Gt. Lakes. Res.* 36 (Suppl. 2), 33–50.

- Chien, Huicheng, Yeh, Pat J.-F., Knauft, Jason H., 2013. Modeling the potential impacts of climate change on streamflow in agricultural watersheds of the midwestern United States. *J. Hydrology* 491 (May 29), 73–88. <http://dx.doi.org/10.1016/j.jhydrol.2013.03.026>.
- Choi, Woonsup, Deal, Brian M., September 2008. Assessing hydrological impact of potential land use change through hydrological and land use change modeling for the kishwaukee river basin (USA). *J. Environ. Manag.* 88 (4), 1119–1130. <http://dx.doi.org/10.1016/j.jenvman.2007.06.001>.
- Chung, Eun-Sung, Park, Kyungshin, Lee, Kil Seong, 2011. The relative impacts of climate change and urbanization on the hydrological response of a Korean urban watershed. *Hydrol. Process.* 25 (4), 544–560. <http://dx.doi.org/10.1002/hyp.7781>.
- Cibin, R., Sudheer, K.P., Chaubey, I., 2010. Sensitivity and identifiability of stream flow generation parameters of the SWAT model. *Hydrol. Process.* 24 (9), 1133–1148. <http://dx.doi.org/10.1002/hyp.7568>.
- Cubasch, U., Wuebbles, D., Chen, D., Facchini, M.C., Frame, D., Mahowald, N., Winther, J.G., 2013. Chapter 1: introduction. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, vols. 119–58 Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Cuo, Lan, Beyene, Tazabe K., Voisin, Nathalie, Su, Fengge, Lettenmaier, Dennis P., Alberti, Marina, Richey, Jeffrey E., 2011. Effects of mid-twenty-first century climate and land cover change on the hydrology of the puget sound basin, Washington. *Hydrol. Process.* 25 (11), 1729–1753. <http://dx.doi.org/10.1002/hyp.7932>.
- Dams, J., Nossent, J., Senbeta, T.B., Willems, P., Batelaan, O., October 2015. Multi-model approach to assess the impact of climate change on runoff. *J. Hydrology* 529 (Part 3), 1601–1616. <http://dx.doi.org/10.1016/j.jhydrol.2015.08.023>.
- El-Khouri, A., Seidou, O., Lapen, D.R., Que, Z., Mohammadian, M., Sunohara, M., Bahram, D., March 15, 2015. Combined impacts of future climate and land use changes on discharge, nitrogen and phosphorus loads for a canadian river basin. *J. Environ. Manag.* 151, 76–86. <http://dx.doi.org/10.1016/j.jenvman.2014.12.012>.
- Fan, Min, Shibata, Hideaki, March 2015. Simulation of watershed hydrology and stream water quality under land use and climate change scenarios in teshio river watershed, northern Japan. *Ecol. Indic.* 50, 79–89. <http://dx.doi.org/10.1016/j.ecolind.2014.11.003>.
- Feyereisen, G.W., Strickland, T.C., Bosch, D.D., Sullivan, D.G., 2007. Evaluation of SWAT manual calibration and input parameter sensitivity in the little river watershed. *Trans. ASABE* 50 (3), 843–855.
- Ficklin, D., Robeson, S.M., Knauft, J.H., 01 2016. Impacts of recent climate change on trends in baseflow and stormflow in United States watersheds. *Geophys. Res. Lett.* 43 (10). <http://dx.doi.org/10.1002/2016GL069121>. 5079–88.
- Ficklin, D.L., Luo, Y., Luedeling, E., Zhang, M., 2009. Climate change sensitivity assessment of a highly agricultural watershed using SWAT. *J. Hydrology* 374 (1–2), 16–29.
- Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S.C., Collins, W., Cox, P., et al., 2013. Chapter 9: evaluation of climate models. In: *Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Franczyk, J., Chang, H., 2009. The effects of climate change and urbanization on the runoff of the rock Creek basin in the portland metropolitan area, Oregon, USA. *Hydrol. Process.* 23 (6) 805–15.
- Galat, D.L., Berry, G.R., Peters, E.J., White, R.G., 2005. Missouri river basin. In: Benke, A.C., Cushing, C.E. (Eds.), *Rivers of North America*. Elsevier Academic Press, pp. 427–480.
- Gassman, Philip W., Sadeghi, Ali M., Srinivasan, Raghavan, 2014. Applications of the SWAT model special section: overview and insights. *J. Environ. Qual.* (1).
- Gassman, P.W., Reyes, M.R., Green, C.H., Arnold, J.G., 2007. The soil and water assessment Tool: historical development, applications, and future research directions. *Trans. ASABE* 50 (4) 1211–50.
- Georgakakos, A., Fleming, P., Dettlinger, M., Peters-Lidard, C., Richmand, T.C., Reckhow, K., White, K., Yates, D., 2014. Chapter 3: Water Resources." *Climate Change Impacts in the United States. The Third National Climate Assessment*, pp. 69–112. <http://dx.doi.org/10.7930/J0J1012N>.
- Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., Tyler, D., 2002. The national elevation dataset. *Photogrammetric Eng. Remote Sens.* 68 (1), 5–11.
- Holvoet, K., van Griensven, A., Seuntjens, P., Vanrolleghem, P.A., 2005. Sensitivity analysis for hydrology and pesticide supply towards the river in SWAT. *Phys. Chem. Earth* 30 (8–10), 518–526. <http://dx.doi.org/10.1016/j.pce.2005.07.006>.
- Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D., Megown, K., 2015. Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. *Photogrammetric Eng. Remote Sens.* 81 (5), 345–354.
- Hubbart, Jason A., Zell, Chris, April 10, 2013. Considering streamflow trend analyses uncertainty in urbanizing watersheds: a baseflow case study in the Central United States. *Earth Interact.* 17 (5), 1–28. <http://dx.doi.org/10.1175/2012EI000481.1>.
- International Livestock Research Institute, 2014. Centro Internacional del Agricultura Tropical, Research Program on Climate Agriculture and Food Security. MarkSim DSSAT weather file generator. <http://gisweb.ciat.cgiar.org/MarkSimGCM/>.
- Jha, Manoj, Arnold, Jeffrey G., Gassman, Philip W., Giorgi, Filippo, Gu, Roy R., August 1, 2006. Climate change sensitivity assessment on upper Mississippi river basin streamflows using Swat1. *JAWRA J. Am. Water Resour. Assoc.* 42 (4), 997–1015. <http://dx.doi.org/10.1111/j.1752-1688.2006.tb04510.x>.
- Jiménez Cisneros, B.E., Oki, T., Arnell, N.W., Benito, G., Cogley, J.G., Döll, P., Jiang, T., Mwakalila, S.S., 2014. Chapter 3: freshwater resources. In: *Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part a: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Jin, X., Sridhar, V., 2012. Impacts of climate change on hydrology and water resources in the boise and spokane river basins. *J. Am. Water Resour. Assoc.* 48 (2), 197–220.
- Joh, H.-K., Lee, J.-W., Park, M.-J., Shin, H.-J., Yi, J.-E., Kim, G.-S., Srinivasan, R., Kim, S.-J., 2011. Assessing climate change impact on hydrological components of a small forest watershed through swat calibration of evapotranspiration and soil moisture. *Trans. ASABE* 54 (5), 1773–1781.
- Jones, P.G., Thornton, P.K., 2013. Generating downscaled weather data from a suite of climate models for agricultural modelling applications. *Agric. Syst.* 114, 1–5. <https://doi.org/10.1016/j.agsy.2012.08.002>.
- Kellner, Elliott, Hubbart, Jason A., October 1, 2016. Continuous and event-based time series analysis of observed floodplain groundwater flow under contrasting land-use types. *Sci. Total Environ.* 566–567, 436–445. <http://dx.doi.org/10.1016/j.scitotenv.2016.05.036>.
- Kim, N.W., Won, Y.S., Lee, J., Lee, J.E., Jeong, J., 2011. Hydrological impacts of urban imperviousness in white rock Creek watershed. *Trans. ASABE* 54 (5), 1759–1771.
- Kumar, D.S., Arya, D.S., Vojinovic, Z., 2013. Modeling of urban growth dynamics and its impact on surface runoff characteristics. *Comput. Environ. Urban Syst.* 41, 124–135. <http://dx.doi.org/10.1016/j.compenvurbysys.2013.05.004>.
- Lin, Yu-Pin, Lin, Yun-Bin, Wang, Yen-Tan, Hong, Nien-Ming, February 4, 2008. Monitoring and predicting land-use changes and the hydrology of the urbanized paochiao watershed in taiwan using remote sensing data, urban growth models and a hydrological model. *Sensors* 8 (2), 658–680. <http://dx.doi.org/10.3390/s8020658>.
- Mas, J.-F., Filho, B., Pontius, R., Gutiérrez, M., Rodrigues, H., 2013. A suite of tools for ROC analysis of spatial models. *ISPRS Int. J. Geo-Information* 2 (3), 869–887. <https://doi.org/10.3390/ijgi2030869>.
- Mishra, V., Cherkauer, K.A., Niyogi, D., Lei, M., Pijanowski, B.C., Ray, D.K., Bowling, L.C., Yang, G., 2010. A regional scale assessment of land use/land cover and climatic changes on water and energy cycle in the upper midwest United States. *Int. J. Climatol.* 30 (13) 2025–44.
- MoDOT. Missouri Department of Transportation MO 2010 October MoDOT Roads/Routes, 2010. Accessed at the Missouri Spatial Data Information Service. <ftp://msdis.missouri.edu/pub/>.
- Mohammed, Ibrahim Nourein, Bombliès, Arne, Beverley, C., Wemple, March 2015. The use of CMIP5 data to simulate climate change impacts on flow regime within the lake champlain basin. *J. Hydrology Regional Stud.* 3, 160–186. <http://dx.doi.org/10.1016/j.ejrh.2015.01.002>.
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* 50 (3), 885–900.
- Moriasi, D.N., Wilson, B.N., Douglas-Mankin, K.R., Arnold, J.G., Gowda, P.H., 2012. Hydrologic and water quality models: use, calibration, and validation. *Trans. ASABE* 55 (4), 1241–1247.
- Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. *Trans. ASABE* 58 (6), 1763–1785. <https://doi.org/10.13031/Trans.58.10715>.
- Neitsch, S.L., Arnold, J., Kiniry, J.R., Williams, J.R., 2011. *Soil and Water Assessment Tool Theoretical Documentation Version 2009: TR-406*. Texas A&M University System.
- Neupane, Ram P., Kumar, Sandeep, October 2015. Estimating the effects of potential climate and land use changes on hydrologic processes of a large agriculture dominated watershed. *J. Hydrology* 529 (Part 1), 418–429. <http://dx.doi.org/10.1016/j.jhydrol.2015.07.050>.
- Nichols, John, Hubbart, Jason A., Poulton, Barry C., June 1, 2016. Using macro-invertebrate assemblages and multiple stressors to infer urban stream system condition: a case study in the central U.S. *Urban Ecosyst.* 19 (2), 679–704. <http://dx.doi.org/10.1007/s11252-016-0534-4>.
- Nigh, T.A., Schroeder, W.A., 2002. *Atlas of Missouri Ecoregions*. State of Missouri. Missouri Department of Conservation.
- Ouyang, Fen, Zhu, Yonghua, Fu, Guobin, Haishen, Lü, Zhang, Aijing, Yu, Zhongbo, Chen, Xi, January 11, 2015. Impacts of climate change under CMIP5 RCP scenarios on streamflow in the huangnizhuang catchment. *Stoch. Environ. Res. Risk Assess.* 29 (7). <http://dx.doi.org/10.1007/s00477-014-1018-9>. 1781–95.
- Paul, M.J., Meyer, J.L., 2001. Streams in the urban landscape. *Annu. Rev. Ecol. Syst.* 32, 333–365.
- Pervez, Md Shahrar, Henebry, Geoffrey M., March 2015. Assessing the impacts of climate and land use and land cover change on the freshwater availability in the brahmaputra river basin. *J. Hydrology Regional Stud.* 3, 285–311. <http://dx.doi.org/10.1016/j.ejrh.2014.09.003>.
- Pontius Jr., R.Gil, Schneider, Laura C., June 2001. Land-cover change model validation by an ROC method for the ipswich watershed, Massachusetts, USA. *Agric. Ecosyst. Environ.* 85 (1–3). [http://dx.doi.org/10.1016/S0167-8809\(01\)00187-6](http://dx.doi.org/10.1016/S0167-8809(01)00187-6). 239–48.
- Pryor, S.C., Scavia, D., Downer, C., Gaden, M., Iverson, L., Nordstrom, R., Patz, J., Robertson, G.P., 2014. Chapter 18: midwest." *climate change impacts in the United States: The Third National Climate Assessment*. pp. 418–440. <http://dx.doi.org/10.7930/J0J1012N>.
- Qi, S., Sun, G., Wang, Y., McNulty, S.G., Moore Myers, J.A., 2009. Streamflow response to climate and landuse changes in a coastal watershed in North Carolina. *Trans. ASABE* 52 (3), 739–749.
- Rahman, Kazi, da Silva, Ana Gago, Tejeda, Enrique Moran, Gobiet, Andreas, Beniston, Martin, Lehmann, Anthony, September 2015. An independent and combined effect analysis of land use and climate change in the upper rhone river watershed, Switzerland. *Appl. Geogr.* 63, 264–272. <http://dx.doi.org/10.1016/j.apgeog.2015.06.021>.
- Redfern, Thomas W., Macdonald, Neil, Kjeldsen, Thomas R., Miller, James D., Nick,

- Reynard, October 1, 2016. Current understanding of hydrological processes on common urban surfaces. *Prog. Phys. Geogr.* 40 (5), 699–713. <http://dx.doi.org/10.1177/0309133316652819>.
- Riahi, Keywan, Rao, Shilpa, Krey, Volker, Cho, Cheolhung, Chirkov, Vadim, Fischer, Guenther, Kindermann, Georg, Nakicenovic, Nebojsa, Rafaj, Peter, August 13, 2011. RCP 8.5—a scenario of comparatively high greenhouse gas emissions. *Clim. Change* 109 (1–2), 33–57. <http://dx.doi.org/10.1007/s10584-011-0149-y>.
- Romero-Lankao, P., Smith, J.B., Davidson, D.J., Diffenbaugh, N.S., Kinney, P.L., Kirshen, P., Kovacs, P., Villers-Ruiz, L., 2014. Chapter 26: North America. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M. (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 1439–98.
- Rossi, C.G., Dybala, T.J., Moriasi, D.N., Arnold, J.G., Amonett, C., Marek, T., November 1, 2008. Hydrologic calibration and validation of the soil and water assessment Tool for the leon river watershed. *J. Soil Water Conservation* 63 (6), 533–541. <http://dx.doi.org/10.2489/jswc.63.6.533>.
- Sanford, Ward E., Selnick, David L., February 1, 2013. Estimation of evapotranspiration across the conterminous United States using a regression with climate and land-cover Data1. *JAWRA J. Am. Water Resour. Assoc.* 49 (1). <http://dx.doi.org/10.1111/jawr.12101>. 217–30.
- Schueler, T.R., Fraley-McNeal, L., Cappiella, K., 2009. Is impervious cover still Important? Review of recent research. *J. Hydrologic Eng.* 14 (4), 309–315.
- Sheshukov, A.Y., Siebenmorgen, C.B., Douglas-Mankin, K.R., 2011. Seasonal and annual impacts of climate change on watershed response using an ensemble of global climate models. *Trans. ASABE* 54 (6), 2209–2218.
- Sun, L., Kunkel, K.E., Stevens, L.E., Buddenberg, A., Dobson, J.G., Easterling, D.R., 2015. Technical Report NESDIS. Regional Surface Climate Conditions in CMIP3 and CMIP5 for the United States: Differences, Similarities, and Implications for the U.S. National Climate Assessment, vol. 144 NOAA <http://dx.doi.org/10.7289/V5RB72KG>. 111 pp.
- Sunde, Michael G., He, Hong S., Hubbard, Jason A., Urban, Michael A., April 30, 2017. Integrating downscaled CMIP5 data with a physically based hydrologic model to estimate potential climate change impacts on streamflow processes in a mixed-use watershed. *Hydrol. Process.* 31 (9), 1790–1803. <http://dx.doi.org/10.1002/hyp.11150>.
- Sunde, Michael G., He, Hong S., Bo, Zhou, Hubbard, Jason A., Anthony, Spicci, April 2014. Imperviousness change analysis Tool (I-CAT) for simulating pixel-level urban growth. *Landsc. Urban Plan.* 124, 104–108. <http://dx.doi.org/10.1016/j.landurbplan.2014.01.007>.
- Sunde, Michael G., He, Hong S., Hubbard, Jason A., Craig, Scroggins, July 2016. Forecasting streamflow response to increased imperviousness in an urbanizing midwestern watershed using a coupled modeling approach. *Appl. Geogr.* 72, 14–25. <http://dx.doi.org/10.1016/j.apgeog.2016.05.002>.
- United States Census Bureau, 2015. Annual Estimates of the Resident Population for Incorporated Places of 50,000 or More, Ranked by July 1, 2015 Population: April 1, 2010 to July 1, 2015 – United States. Retrieved from: <http://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml/>.
- USDA. Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at: <http://websoilsurvey.nrcs.usda.gov/>. Accessed [2015].
- USGS. Coordinated effort between the U.S. Geological Survey and U.S. Environmental Protection Agency, 1999. National Hydrography Dataset (State of Missouri). Available URL: <http://nhd.usgs.gov/> Accessed [2015].
- Viger, R.J., Hay, L.E., Markstrom, S.L., Jones, J.W., Buell, G.R., 2011. Hydrologic effects of urbanization and climate change on the flint river basin, Georgia. *Earth Interact.* 15 (20), 1–25.
- Vo, Ngoc Duong, Gourbesville, Philippe, Vu, Minh Tue, Raghavan, Srivatsan V., Liong, Shie-Yui, June 2016. A deterministic hydrological approach to estimate climate change impact on river flow: vu gia-thu bon catchment, vietnam. *J. Hydro-Environment Res.* 11, 59–74. <http://dx.doi.org/10.1016/j.jher.2015.11.001>.
- Vuuren, Detlef P. van, Edmonds, Jae, Kainuma, Mikiko, Riahi, Keywan, Thomson, Allison, Hibbard, Kathy, Hurtt, George C., et al., 2011. The representative concentration pathways: an overview. *Clim. Change* 109 (1–2), 5–31. <http://dx.doi.org/10.1007/s10584-011-0148-z>.
- Walsh, J., Wuebbles, D., Hayhoe, K., Kossin, J., Kunkel, K., Stephens, G., Thorne, P., et al., 2014. Chapter 2: Our Changing Climate.” *Climate Change Impacts in the United States*, vols. 19–67 The Third National Climate Assessment <http://dx.doi.org/10.7930/J0KW5CXT>.
- Wang, R., Cherkauer, K.A., Bowling, L.C., Cibin, R., Her, Y., Chaubey, I., 31 2017. Biophysical and hydrological effects of future climate change including trends in CO₂, in the st. Joseph river watershed, eastern corn belt. *Agric. Water Manag.* 180, 280–296. <http://dx.doi.org/10.1016/j.agwat.2016.09.017>.
- Wang, Ry, Kalin, L., Kuang, Wh, Tian, Hq, November 30, 2014. Individual and combined effects of land use/cover and climate change on wolf bay watershed streamflow in southern Alabama. *Hydrol. Process.* 28 (22), 5530–5546.
- Wei, L., Hubbard, J.A., Zhou, H., 2018. Variable streamflow contributions in nested subwatersheds of a US midwestern urban watershed. *Water Resour. Manag.* 32 (1), 213–228. <https://doi.org/10.1007/s11269-017-1804-5>.
- White, K.L., Chaubey, I., 2005. Sensitivity analysis, calibration, and validations for a multisite and multivariable SWAT model. *J. Am. Water Resour. Assoc.* 41 (5), 1077–1089.
- Wilson, Cyril O., Weng, Qihao, September 15, 2011. Simulating the impacts of future land use and climate changes on surface water quality in the des plaines river watershed, chicago metropolitan statistical area, Illinois. *Sci. Total Environ.* 409 (20), 4387–4405. <http://dx.doi.org/10.1016/j.scitotenv.2011.07.001>.
- Wolock, D.M., 2003. Base-flow Index Grid for the Conterminous United States. U.S. Geological Survey Open-file. Report 03–263. U.S. Geological Survey. https://doi.org/OpenFileRep_03-263.
- Wu, F., Zhan, J., Güneralp, I., 2015. Present and future of urban water balance in the rapidly urbanizing heihe river basin, northwest China. *Ecol. Model.* 318, 254–264. <http://dx.doi.org/10.1016/j.ecolmodel.2014.11.032>.
- Xian, G., Homer, C., Dewitz, J., Fry, J., Hossain, N., Wickham, J., 2011. Change of impervious surface area between 2001 and 2006 in the conterminous United States. *Photogrammetric Eng. Remote Sens.* 77 (8), 758–762.
- Xu, C.-Y., 1999. From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches. *Prog. Phys. Geogr.* 23 (2), 229–249.
- Xu, Yue-Ping, Zhang, Xujie, Ran, Qihua, Tian, Ye, March 13, 2013. Impact of climate change on hydrology of upper reaches of qiantang river basin, east China. *J. Hydrology* 483, 51–60. <http://dx.doi.org/10.1016/j.jhydrol.2013.01.004>.
- Zeiger, Sean J., Hubbard, Jason A., December 1, 2016a. A SWAT model validation of nested-scale contemporaneous stream flow, suspended sediment and nutrients from a multiple-land-use watershed of the Central USA. *Sci. Total Environ.* 572, 232–243. <http://dx.doi.org/10.1016/j.scitotenv.2016.07.178>.
- Zeiger, Sean J., Hubbard, Jason A., May 15, 2016b. Nested-scale nutrient flux in a mixed-land-use urbanizing watershed. *Hydrol. Process.* 30 (10), 1475–1490. <http://dx.doi.org/10.1002/hyp.10716>.
- Zhou, Bo, He, Hong S., Nigh, Timothy A., Schulz, John H., August 2012. Mapping and analyzing change of impervious surface for two decades using multi-temporal landsat imagery in Missouri. *Int. J. Appl. Earth Observation Geoinformation* 18 (0), 195–206. <http://dx.doi.org/10.1016/j.jag.2012.02.003>.